# HIGH BEDROCK INCISION RATES IN THE ATENGUILLO RIVER VALLEY, JALISCO, WESTERN MEXICO

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## ABSTRACT

Lava flows from three basaltic shield volcanoes preserve Pliocene–Pleistocene river levels in the Atenguillo River basin, western Mexico. K–Ar dates of these basalt flows, together with present and palaeoriver levels, allow calculation of bedrock incision rates at three points along the length of the Atenguillo River: at Volcan La Laja, dated at 0·65 Ma, incision rates are 25 cm $ka^{-1}$; at Volcan La Cienega (2·2 Ma) incision rates are 23 cm $ka^{-1}$; and at Volcan El Vigia (2·7 Ma) incision rates are 23 cm $ka^{-1}$. These high incision rates, as well as two distinct knickpoints along the profile of the Atenguillo River, are related to a base level change at the northern end of the basin. The dynamics of this river basin are controlled by the ongoing process of continental fragmentation associated with the opening of the Gulf of California. © 1997 by John Wiley & Sons, Ltd.

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## INTRODUCTION

The incision of rivers into bedrock is a poorly understood process. Although incision rates have been measured in several localities, the variables involved are not easily distinguished from one another. Recent work by Seidl and Dietrich (1992) indicates that incision rates are related to the drainage area and slope of a given basin and river system. Other studies have demonstrated the importance of sediment transport mechanisms and the characteristics of the sediment bed flow (Begin *et al*., 1980). In order to evaluate models for determining and predicting bedrock incision rates, there must be natural data sets with which to test the models. The purpose of this study is to provide such an example by presenting bedrock incision rates into Cretaceous rhyolitic ash flow in western Mexico. These units comprise the basement of the currently active western Mexican Volcanic Belt (MVB), which is produced by subduction of the Rivera and Cocos Plates beneath the North American Plate (Figure 1). Although one might expect a relation between bedrock incision rates, rock strength, sediment load and rock type, an understanding of these factors remains to be quantified. Studies must be completed on a wide variety of river settings before such a task may be attempted, and it is hoped that this study will provide such information for future research.

## THE WESTERN MVB AND ATENGUILLO VALLEY

The western MVB is an active volcanic arc. Much of the Pliocene to Holocene volcanism in the region is focused into a series of grabens and fault-bounded valley (Figure 1). The faulting is thought to be related to the changing offshore plate boundaries, the possible migration of the East Pacific Rise onto the Mexican continent (Luhr *et al*., 1985; Allan *et al*., 1991), and possibly oblique subduction of the Rivera Plate (DeMets and Stein, 1990). One of these grabens, the Atenguillo graben, is oriented N–S and is the site of extensive basaltic volcanism (Figure 2; Righter and Carmichael, 1992). This Pliocene to Pleistocene volcanic activity has produced several medium-sized shield volcanoes and plateaus (Righter and Carmichael, 1992). In several

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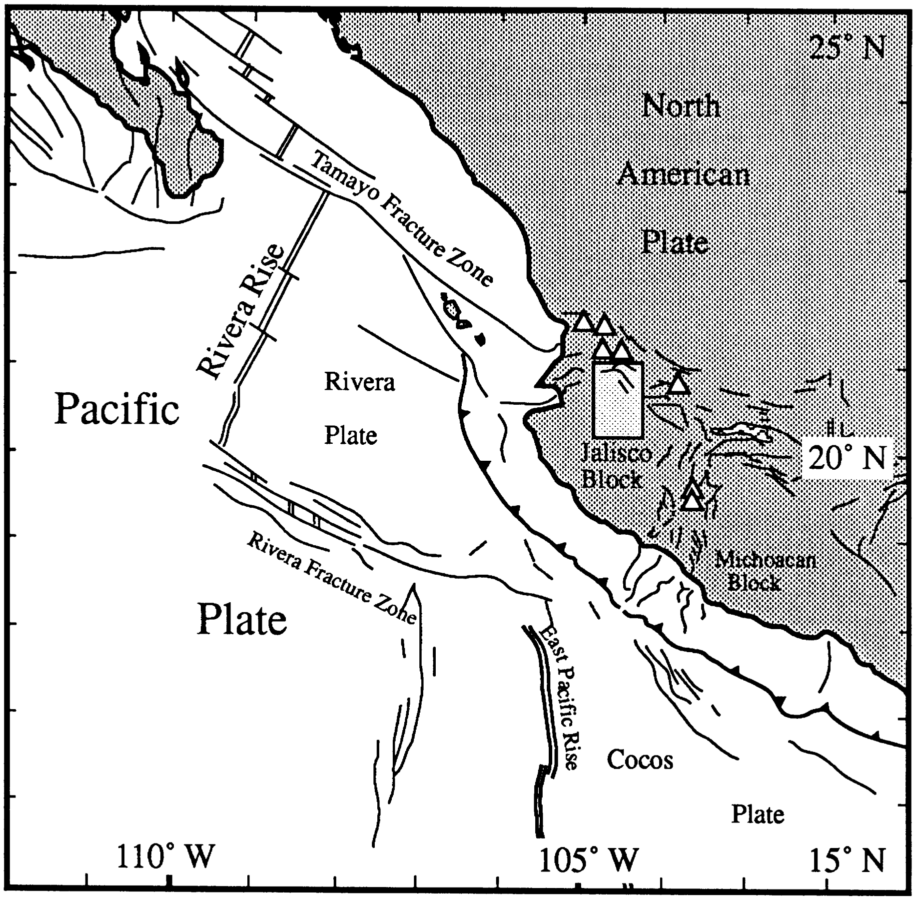


Figure 1. Map of western Mexico showing offshore plate boundaries (Ness and Lyle, 1991), onshore normal faults (after Johnson and Harrison, 1989), and the Jalisco and Michoacan Blocks. The light shaded area is the Atenguillo valley, enlarged in Figure 2. The fault with triangles along the length is the Middle America Trench. Open triangles are central volcanoes within the Mexican Volcanic Belt

localities, lava flowed into the basin (in some cases overtop of river gravels), thus preserving the Pliocene to Pleistocene river levels. The Atenguillo River cuts through many of these volcanic units as it flows north and joins the Ameca River. At one point along the Atenguillo, there is 1 km of relief from river level to the top of the shield volcano, Volcan La Cienega. Since at least the Pleistocene, the Atenguillo River has been cutting down through the young volcanic cover and the Cretaceous ash flows (Righter *et al.*, 1995) that make up the walls and floor of the graben, thus exposing the old river levels. In three cases, the volcanic units just above the old river levels have been dated, allowing estimates to be made of the river incision rates along the length of the Atenguillo valley.

## INCISION RATES

### *Volcan La Laja*

Volcan La Laja is a Pleistocene (0·65 Ma) shield volcano, 5 km in diameter, with a volume of nearly 10 km$^3$ (Righter and Carmichael, 1992). From geological information collected around the perimeter of the volcano, it is clear that it erupted into a broad river valley. The basalt flows overlie a sequence of river gravel and sediments that preserve features such as cross-stratification and lenticular sand bars. As the shield formed, it dammed the Atenguillo River, thus forming a lake. Evidence for this is in the form of lake sediments south of Volcan La Laja, and pillow lavas on its southeast flank (Righter and Carmichael, 1992). The early basalt flows at the volcano, then, mark the palaeoriver elevation for the Atenguillo River (Figure 3). The underlying fluvial

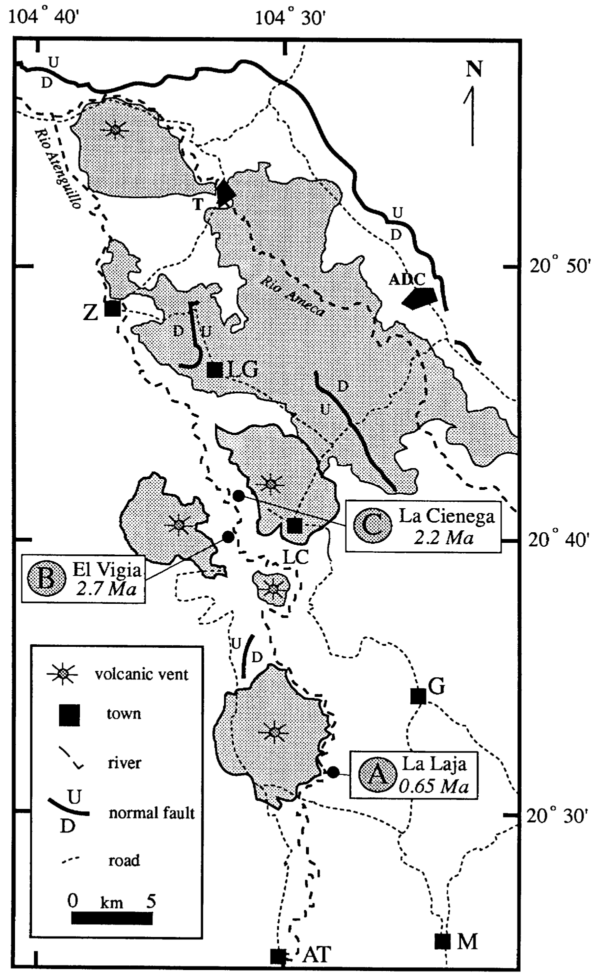


Figure 2. Map of the Atenguillo valley, showing location of towns: Tepuzuacan (T), Amatlan de Canas (ADC), Zacatongo (Z), Llano Grande (LG), La Cienega (LC), Guachinango (G), Mixtlan (M), and Atenguillo (AT). Shaded areas are Plio-Quaternary volcanic rocks described by Righter and Carmichael (1992). Stratigraphic columns at sites A, B and C (shown in Figure 3) were constructed from data collected near each of the solid dots located in the valley. The Ameca River flows through the western part of the Amatlan de Canas Tectonic Depression. Heavy solid lines are normal faults with up (U) and down (D) blocks indicated. Ages of the volcanoes are from Righter and Carmichael (1992)

sediments are at an elevation of 1250 m, and the current river elevation at that point is 1100 m. Incision of 150 m in 0·65 Ma yields a mean incision rate of 25 cm $ka^{-1}$.

*Volcan La Cienega*

Pliocene (2·2 Ma) Volcan La Cienega may have dammed the Atenguillo River as well. The flanks of La Cienega are at an elevation of approximately 1500 m. At the same elevation, south of La Cienega and near the town of Mixtlan, there are thin lacustrine sediments (Righter and Carmichael, 1992). These are too high to be associated with the lake formed by Volcan La Laja. The Atenguillo canyon walls start near the summit of La Cienega; the river has cut nearly 1 km deep there. Exposed in the section is an extensive sequence of basic lava flows, underlain by 80–100 m of pyroclastic deposit (Figure 3). The palaeoriver level has been estimated by sighting over to the base of the volcano from the west side, near the town of El Vigia. The base of the volcano is at an elevation of 1300 m, and the current river level is at 800 m (Figure 3). Incision of 500 m in 2·2 Ma results in a mean incision rate of 23 cm $ka^{-1}$.

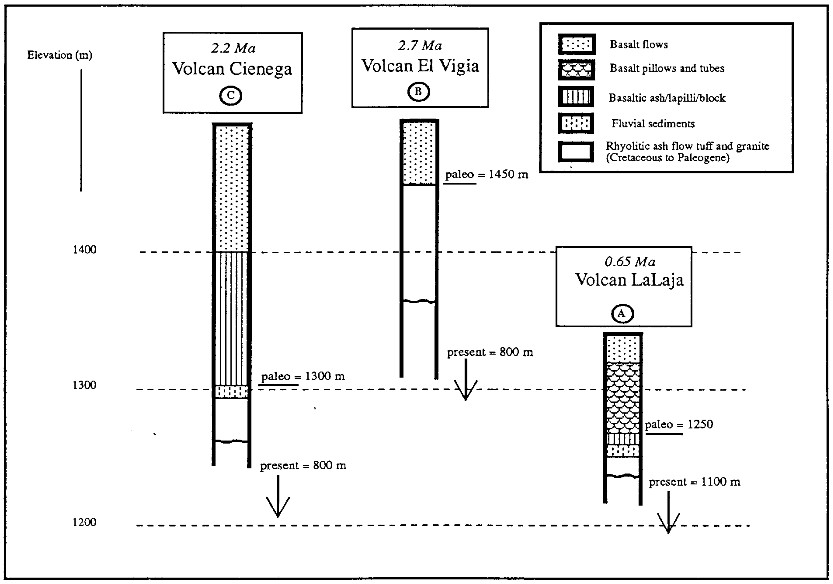


Figure 3. Stratigraphic columns constructed from data collected at the three sites located on Figure 2. 'Paleo' indicates the current elevation of the palaeoriver level capping the lava flow, and 'present' indicates the present river elevation in the channel

### *Volcan El Vigia*

The stratigraphy at Pliocene (2·7 Ma) Volcan El Vigia is well exposed in the Atenguillo canyon, but not as accessible. However, an estimate can be made of the basal elevation of the volcano by siting over from the flanks of Volcan La Cienega (Figure 3). Volcan El Vigia is constructed of approximately eight to ten basalt flows. The base of the volcano is at an elevation of 1450 m, while the river level is at 800 m. This amount of incision corresponds to a mean incision rate of 23 cm $ka^{-1}$

## KNICKPOINTS

An elevation profile for the Atenguillo River has been constructed from the CETENAL series of topographic maps (Maps F13D-61 Amatlan de Canas, 71 Guachinango and 81 Atenguillo). The 140 km length of the profile exhibits two distinct changes in gradient (Figure 4A), which correspond to the spikes in slope (Figure 4B). The large increase in the wall elevation at 30 km is the summit wall of Volcan La Cienega. The changes in slope, or knickpoints (one at *c*. 70 km and one at *c*. 100 km), do not correspond to changes in lithology along the channel, as the entire length of the channel is Cretaceous to early Cenozoic rhyolite and ashflow (except for a thin basalt veneer in some places), nor do they correspond to the junction of tributary streams.

There is some controversy over whether knickpoints propagate upstream (Seidl and Dietrich, 1992; Begin *et al*., 1980), or whether they remain stationary and form due to local sediment transport and bedload factors (Young and McDougall, 1993). The latter hypothesis seems unlikely in this case, because sedimentological factors in the Atenguillo basin are faily homogeneous – the bedrock in both the basin and the tributaries is Cretaceous to Paleocene volcanic ash flow. The Atenguillo basin has formed in response to Miocene to Recent tectonism in the western Mexican Volcanic Belt. It is more likely that the knickpoints have been caused by base level changes at the north end of the Atenguillo (where it joins the Ameca River), or by a faulted section along the length of the river.

The Atenguillo River flows northward into the Ameca River (Figure 2). The Ameca flows through the Amatlan de Canas Tectonic Depression (ATD), an E–W oriented feature that has formed in response to normal faulting along the Sierra Guamuchil range (Nieto-Obregon *et al*., 1992). Based on geomorphological features (triangular-shaped facets on the range front, hot springs and deposits of coarse alluvial material (Nieto-Obregon *et al*., 1992)), historic earthquakes (Suarez *et al*., 1994), global positioning system (GPS) measurements

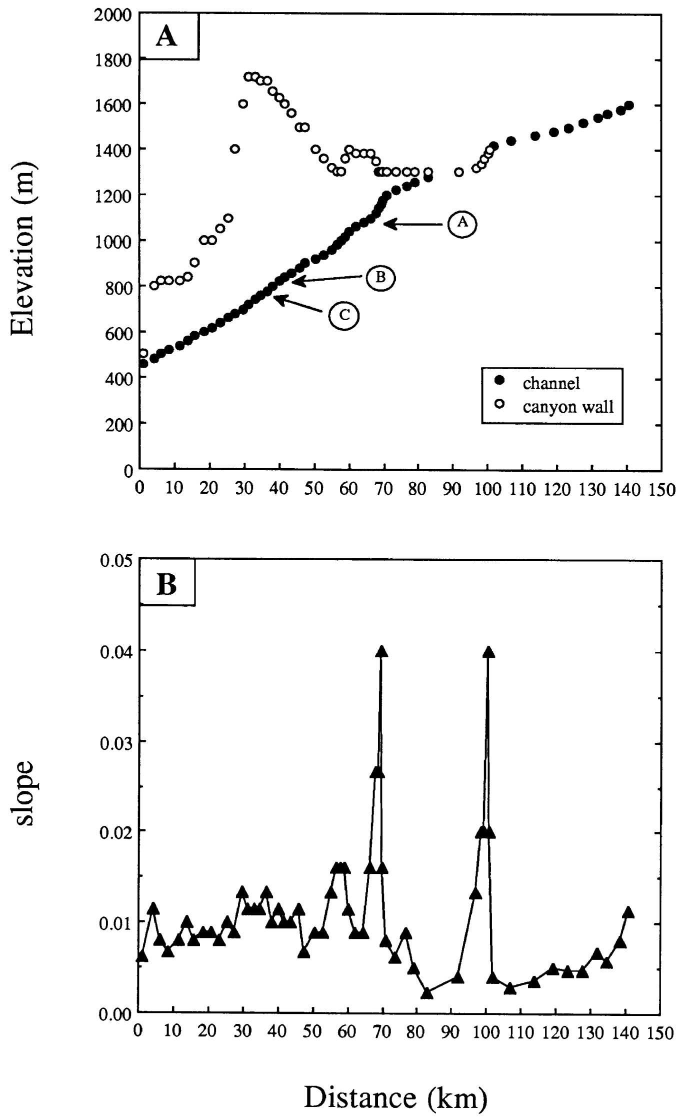


Figure 4. Channel profile (A) and slope (B) data from the Atenguillo River, constructed from the CETENAL series of 1:50 000 topographic maps (Maps F13D81 Atenguillo, 71 Guachinango, and 61 Amatlan de Canas)

(Melbourne *et al.*, 1996), and radiometric dates of faulted lava flows (Righter and Carmichael, 1992; Righter *et al.*, 1995), the faults forming the ATD have been active in the Pleistocene to Recent. If the knickpoints formed at the confluence of the Ameca and Atenguillo Rivers in response to base level changes imposed by the Ameca valley, then they may have migrated upstream to their present positions. If the knickpoints formed 2·7 Ma, they have migrated at most 100 km in that time; this corresponds to a mean propagation rate of 36 m $ka^{-1}$. Such a value seems high compared to knickpoint migration rates estimated in Hawaiian channels (basalt) of 0·5 to 2·0 m $ka^{-1}$ (Seidl *et al.*, 1994). It is possible that knickpoint propagation rates through less dense and cohesive ash flow will be greater than those through basalt flows, but so far such factors are unquantifiable. Also, the knickpoints may smooth out over such large (100 km) propagation distances, in contrast to the distinct slope changes in Figure 4b.

It seems most likely that the knickpoints have formed along the length of the Atenguillo River, south of the Ameca, in response to a faulted section. Such an idea is consistent with the lower propagation rates suggested in

Table I. Comparison of incision rates for the Atenquillo River with other areas

| Locality | Tectonic characteristics | Incision rate ($cm\,ka^{-1}$) | Reference |
|---|---|---|---|
| Atenguillo River | Plio-Quaternary extension | 23–25 | This study; Righter *et al.* (1995) |
| Grand Canyon | Plio-Quaternary extension | 9–10·5 | Damon *et al.* (1974) |
| Sierra Nevada | Cenozoic uplift | 9 | Huber (1981) |
| Utah | Plio-Quaternary extension | 30 | Hamblin *et al.* (1981) |
| Rio Grande Rift | Plio-Quaternary extension | 0·8–8 | Grim (1982) |
| Israel | Extension | 10 | Wohl *et al.* (1994) |
| Hawaii | Ocean islands | 0·5–8 | Seidl *et al.* (1994) |

other studies, and with field observations in the Atenguillo valley. There are several areas (Mesa Llano Grande, and just north of Volcan La Laja; Figure 2) where faults have cut Pliocene–Pleistocene lava flows, indicating young tectonic activity in the basin. The offset along these faults may be responsible for the knickpoints observed upstream within the basin.

There are comparably high incision rates reported for other areas undergoing extension, such as the southwestern US (Grand Canyon, Utah and Rio Grand Rift) and the Dead Sea Rift (Table I). In such tectonic areas, river channels are more likely to undergo base level changes due to normal faulting, and thus high incision rates may be characteristic of river channels at the edge of extensional regimes.

## IMPLICATIONS FOR EXTENSION AND REGIONAL UPLIFT

The high incision rates are related to extension at the edges of the Jalisco Block of western Mexico (see DeMets *et al*., 1995; Righter *et al*., 1995; Melbourne *et al*., 1996), a crustal block that has developed during the process of continental fragmentation that transferred the Baja California peninsula from mainland Mexico to its current position (Stock and Hodges, 1989). There are several lines of geological evidence indicating that this extension is coupled with Cenozoic uplift in the region, including raised Pliocene to Pleistocene marine sediments on the southern coast, between Puerto Vallarta and Manzanillo (Durham *et al*., 1981), exposed Cretaceous to Paleocene schists, phyllites and mid-crustal plutons within the Jalisco Block, and the absence of the young Sierra Madre Occidental ash flows in the Jalisco Block (Righter *et al*., 1995). If all of the late Cenozoic silicic ash flows of the Sierra Madre Occidental were originally present on the Jalisco Block, and have been stripped off due to uplift and erosion, nearly 2000 m (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979; Clark, 1974) of ash flow may have been eroded. Furthermore, areas such as New Zealand and Japan have correlated denudation (based on bedrock incision) and uplift rates (see Summerfield, 1991, pp. 398–393). Although independent estimates of uplift are not available for western Mexico, GPS studies (e.g. Melbourne *et al*., 1996), apatite fission-track dating studies, and cosmogenic isotope studies may ultimately yield important information.

## CONCLUSIONS

Bedrock incision rates in western Mexico have been determined at three localities, and range from 23 to 25 $cm\,ka^{-1}$. Upstream from the three localities are two knickpoints within Cretaceous ash flow tuff. These high incision rates and knickpoints are most likely due to base level lowering along the channel of Atenguillo River, in response to extension and tectonism at the edge of the Jalisco Block in western Mexico.

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